Modeling A Piezoelectric TSM Sensor to study Kinetics of Multi-layer Biosensing Structure

Piyushkumar Shah[1], Dr. Ryszard Lec[1], Sun Jong Kwoun[1]
[1]School of Biomedical Engineering and Health Sciences, Drexel University, Philadelphia, PA, USA

Abstract— **Most of the biological processes are surface mediated; but limited techniques are available to study interfacial biological processes. These techniques exhibit significant limitation due to their low sensitivity and selectivity, and poor temporal resolution. We are studying a novel measurement technique which utilizes piezoelectric thickness shear mode (TSM) sensor for the study of interfacial biological processes in real time. A typical real-life biological system is a multi-layer system comprising of several biological surfaces or interfaces. This multi-layer sensing structure loaded on piezoelectric TSM sensor has been simulated based on Mason's model, which represents each layer as T-network of acoustic and electrical impedances. Each layer is described by its mechanical properties (stiffness, viscosity, density) and geometrical properties (thickness). These properties can be varied for a variety of material parameters which represent broad range of biologically relevant operation conditions. Our model predicts the changes in the total impedance of the sensor system, which is related to the resonance frequency and amplitude of the sensor. In turn, these changes can be related to the ongoing biological processes. The study shows three different processes simulating interfacial phenomena and gelation (solidification) of materials.**

Keywords— **Biosensor, Multilayer, Piezoelectric, TSM**

I. INTRODUCTION

Practical biosensors are multi-layer structures loaded on transducer surfaces. These biological surfaces or layers could be cells [8], DNA, antibodies, etc. put on or suspended in collagen, albumin, nano fibers [9], blood plasma or other biological mediums. Also, most of the biological processes are surface driven. To measure or understand such interfacial processes, measuring technique which is capable of providing information from different depths and interfaces is needed. We propose a piezoelectric Thickness Shear Mode (TSM) sensing technique operating at various harmonic frequencies to be such a technique, which can measure various interfacial biological processes in a multiple biolayer structure.

A TSM sensor is excited in shear mode (displacement parallel to the face of the sensor) to vibrate at its resonant frequency [10]. The magnitude of the resonant frequency will change in response to different properties of load on the TSM sensor. According to Sauerbrey [1], thickness and physical properties of the solid material on a TSM sensor can be related to change in its resonant frequency. This has been applied in various industries to find thickness of solid thin films. Kanazawa [2] devised equation which relates change in resonant frequency to the viscosity and density of Newtonian liquid load on a TSM sensor.

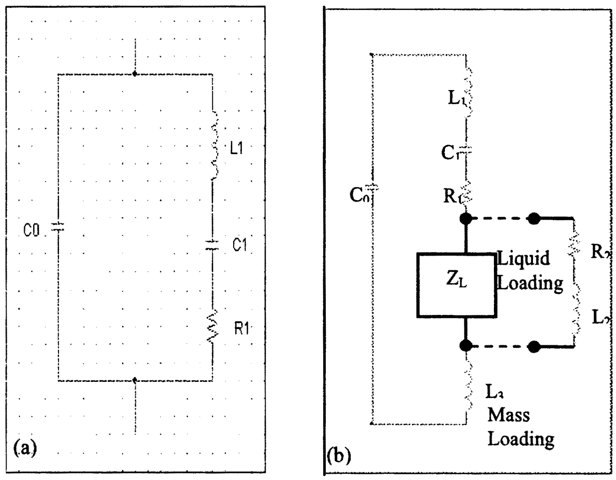

Figure 1. Butterworth-Van Dyke equivalent circuit model of piezoelectric transducer, a) Unloaded case b) Loaded with viscous or mass load. Z_L represents load impedance for liquid load.

Piezoelectric sensor is modeled in various configurations [3]. The representation of unloaded and loaded piezoelectric sensor in form of Butterworth-Van Dyke equivalent circuit model is shown in Figure 1(a) and (b) respectively. As seen in Figure 1(b), total impedance of motional branch includes load impedance Z_L, which varies according to various properties of load on the sensor. This method allows one to analyze the sensor for very thin film load on the sensor surface, by measuring the mechanical (acoustic) impedance of the motional branch of the sensor [4].

Another approach to analyze piezoelectric sensor loaded with thin layer is to solve wave equations and piezoelectric constitutive equations depending on the boundary conditions at each interface [2]. Finally, all the equations can be reduced to algebraic equations, but it is cumbersome to solve them for multiple layers.

The approach used in this paper to model multiple biolayers on a piezoelectric TSM sensor is using Mason's transmission line model [5]. Each layer of load can be represented as a T-network of impedances shown in Figure 2. This model represents each nonpiezoelectric biolayer as 2x2 matrix; hence additional biolayers can be added by cascading another 2x2 matrix for each additional biolayer.

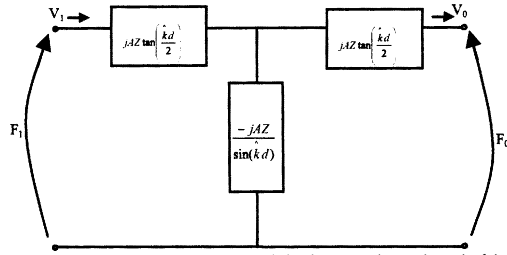

Figure 2. Two-Port Mason Model of a nonpiezoelectric biolayer [5]

Assumptions included in this model are uniform layer thickness, no miscibility between biolayers at interfaces, and one-dimensional motion of the piezoelectric sensor.

II. THEORY

Mason model can also represent piezoelectric crystal with two acoustic ports and one electrical port, which can be simplified to yield two-port equivalent-circuit model of the piezoelectric sensor as shown in Figure 3.

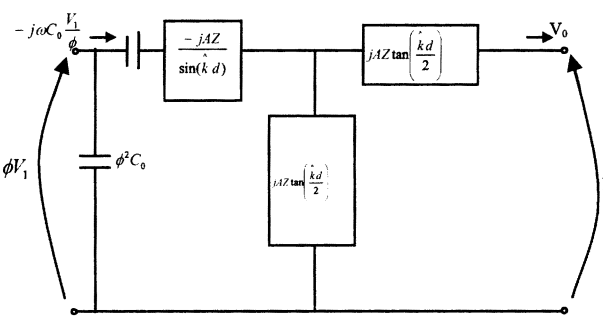

Figure 3. Two-port Mason Model of piezoelectric sensor with one stress-free interface [4][5]

A simple implementation of Mason model for piezoelectric sensor loaded with two layers can be given by equation (I) which express the output current and voltage as a linear function of the input current and voltage and the acoustic parameters of the layers [4].

$$\begin{bmatrix} V_0 \\ I_0 \end{bmatrix} = \begin{bmatrix} A_1 B_1 \\ C_1 D_1 \end{bmatrix} \begin{bmatrix} A_2 B_2 \\ C_2 D_2 \end{bmatrix} \begin{bmatrix} A_q B_q \\ C_q D_q \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \quad \text{(I)}$$

This kind of structure with two nonpiezoelectric layers loaded on piezoelectric sensor plate can be represented by Mason's model as shown in Figure 4.

Here, A, B, C and D in equation (I) represent corresponding transformation matrix entries which relate material properties and convert acoustical parameters to electrical parameters and vice versa. From equation (I), we can find total mechanical impedance of the composite resonator as shown in equation (II).

$$Z_e = \frac{V_0}{I_0} = \frac{A_q V_q + B_q I_q}{C_q V_q + D_q I_q} \quad \text{(II)}$$

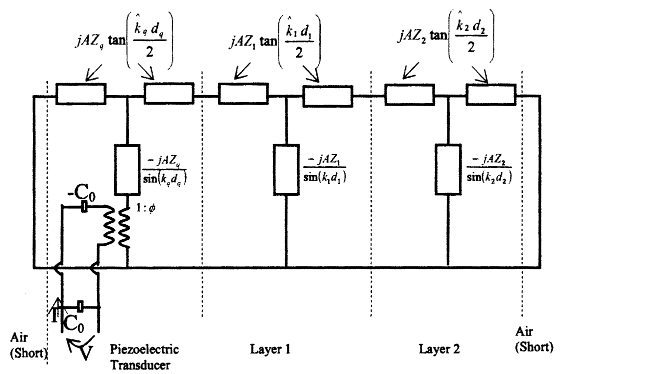

Figure 4. Mason model representation of two nonpiezoelectric layers loaded on piezoelectric plate [5][4]

For complete mathematical derivation and explanation please refer [4]. This impedance corresponds to the motional arm impedance of the BVD circuit shown in Figure 1. Thus, when we calculate this impedance for a range of frequency, minimum impedance will correspond to the resonant frequency [6] of the composite resonator.

For viscous loading, Kanazawa [2] derived the equation for depth of penetration of shear wave into the liquid, which is shown in equation (III).

$$\delta = \left(\frac{2\eta}{\omega\rho} \right)^{1/2} \quad \text{(III)}$$

Also, Figure 5 shows as the harmonic frequency of the piezoelectric plate increases, depth of penetration of the shear wave decreases.

We use this concept of depth of penetration and combine with Mason's model to demonstrate that the information at various boundaries can be captured or measured using piezoelectric quartz sensor operating in thickness shear mode.

We modeled a hypothetical ten layer liquid structure loaded on a piezoelectric sensor, where we can change the mechanical (viscosity, stiffness, density) and geometrical (thickness) properties of each layer, depending on the biological phenomena we want to study. The schematic of such a structure is shown in Figure 6.

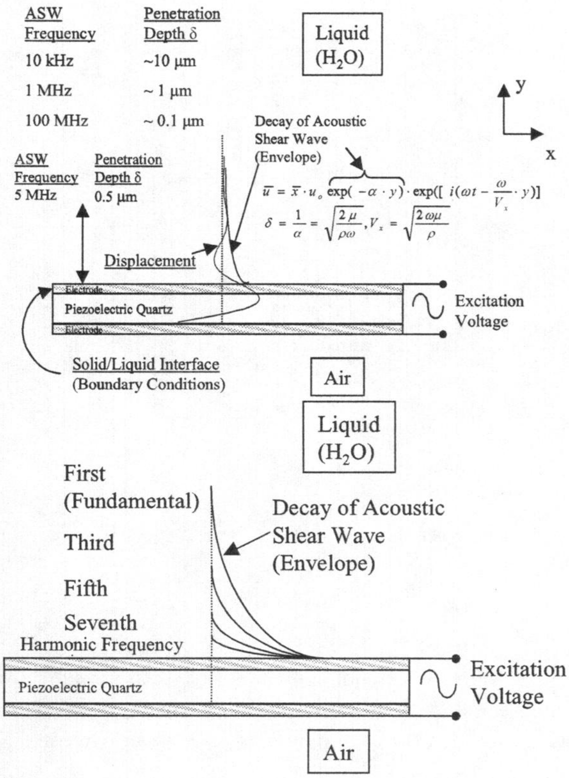

Figure 5. Depth of penetration for (a) fundamental and (b) harmonic resonant frequencies [7]

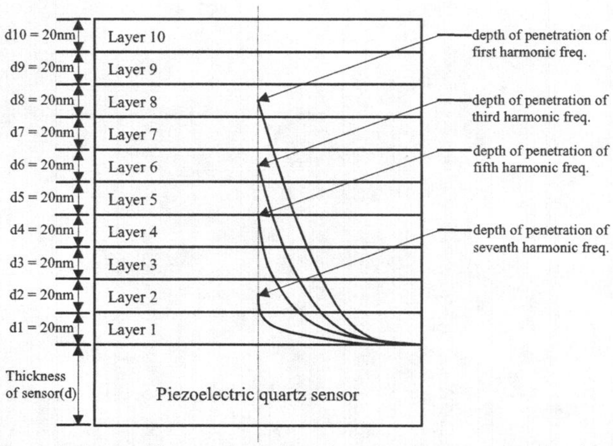

Figure 6. Ten liquid layers loaded on piezoelectric sensor showing depth of penetration for harmonics

The total impedance of the composite resonator formed by ten layers of liquid on piezoelectric sensor (shown in Figure 6) has been calculated using equation (II) for a specified range of frequencies. And then the resonant frequency corresponding to the minimum impedance of the total system has been determined.

$$S_{21} = \frac{50}{50 + Z_e} \tag{IV}$$

Also, this impedance is converted to S-parameter using equation (IV). S_{21} represents the transmission parameter of piezoelectric plate, when connected to measuring devices like network analyzer.

The amplitude and phase of S_{21} represents the amplitude and phase of vibration of piezoelectric plate when excited with electrical voltage at various frequencies [9]. Figure 7 shows such a plot of amplitude and phase versus frequency.

III. RESULTS AND DISCUSSIONS

The response of the piezoelectric sensor depends on the load parameters. The change in viscosity, stiffness, density and thickness of the layers above piezoelectric sensor changes the resonant frequency of the composite resonator [2]. Also, the change in viscosity and density of viscous liquid load, changes the depth of penetration of the shear wave generated by the piezoelectric sensor as shown by equation (III).

Figure 7 shows the response of the piezoelectric sensor for unloaded and loaded case. Load in this case is ten layers of water, each with thickness of 20nm. The change in the resonant frequency (f_r'-f_r) is equal to negative 2800 Hz. Also, note that the depth of penetration of 10 MHz piezoelectric shear wave in water is approximately 180nm from equation (III). Viscosity of water = 0.001 Kg/m-sec., Density of water = 1000 Kg/m^3, Stiffness of water = 1 (approx. zero) N/m^2.

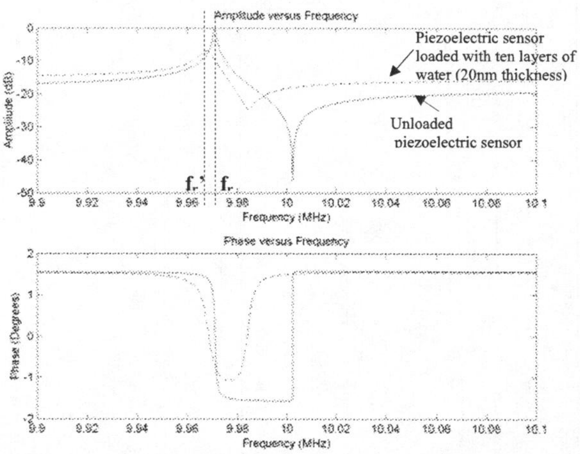

Figure 7. Simulated response of a piezoelectric sensor (10MHz) loaded with ten layers of water each with thickness 20nm

According to Kanazawa [2] change in resonant frequency for infinite water load on the sensor is calculated theoretically as approximately 2100 Hz for 10 MHz crystal.

In this model, if we increase thickness of water loaded on piezoelectric sensor, much higher than depth of penetration (>>180nm), we get change in resonant frequency to be 2150 Hz. This validates our model.

Three different kinds of processes have been simulated using this model. Considering Figure 6, if some processes are going on at layer 6, we should be able to detect and measure it. Hence, as shown in Figure 9, we measured the change in resonant frequency of piezoelectric sensor due to the change in viscosity (from 0.001 to 0.1 Kg/m-sec.) of individual layer (Figure 8). Figure 9 shows the trend observed for change in resonant frequency at various harmonics.

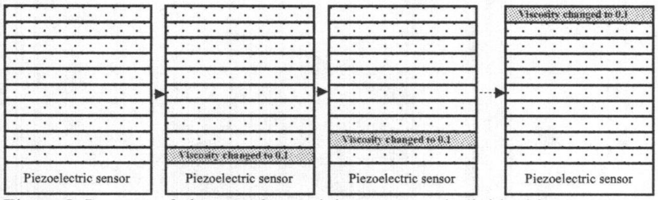

Figure 8. Process of change of material property at individual layer

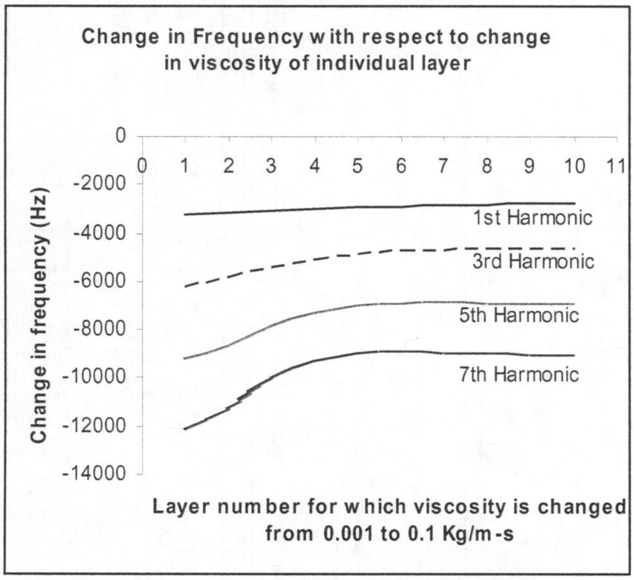

Figure 9. Response of sensor at various harmonics for process shown in Figure 8

There is a linear decrease in change of frequency for lower harmonics during process indicated in Figure 8, whereas a sharp decrease followed by plateau is observed for higher harmonics for the same process as shown in Figure 9. This can be explained with reference to depth of penetration shown in Table 1.

It is clear that the higher the harmonic frequency is, the lower the depth of penetration (Table 1). Then, the change in viscosity of the top layers of the ten-layer structure does not affect the higher harmonics, causing plateau in Figure 9.

Also, since the depth of penetration for higher harmonics is lower, changes in viscosity of the layers near to the surface of the sensor affect greatly the response of higher harmonics, resulting in steeper slopes in that area compared those of lower harmonics. This measurement process shows the capacity of this model to obtain the information at various interfaces depending on the change in material properties. Also, the information can be obtained at various depths simultaneously using harmonics.

Table 1. Depth of penetration of shear wave in water

Water: Viscosity = 0.001 Kg/m-sec, Density = 1000 Kg/m^3		
	Resonant Frequency (MHz)	Depth of Penetration (nm)
First Harmonic	10	178
Third Harmonic	30	103
Fifth Harmonic	50	80
Seventh Harmonic	70	67

Another process simulated is shown in Figure 10. This process is similar to gelation (solidification) process of liquid load.

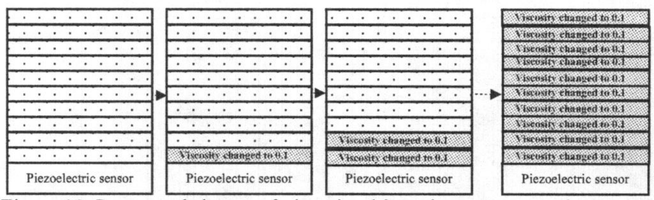

Figure 10. Process of change of viscosity driven from sensor surface to top surface

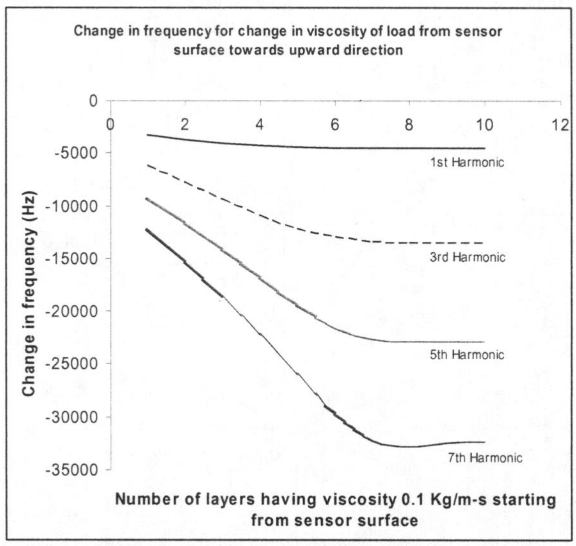

Figure 11. Response of sensor at various harmonics for process shown in Figure 10

The process started with the increase in viscosity of layer 1 (layer touching sensor surface). As the process progresses, viscosity of all layers increases gradually.

The response of the piezoelectric sensor to the process shown in Figure 10 is shown in Figure 11. Again, using Table 1, we can see that as the higher harmonics have lower depth of penetration, the response of piezoelectric sensor is sensitive at lower depth for higher harmonics. Thus, a change at higher depth does not affect the response of piezoelectric sensor, giving plateau at that region.

Similar process was also simulated for top surface driven increase in viscosity, process shown in Figure 12.

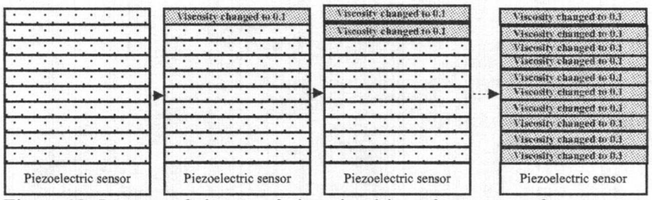

Figure 12. Process of change of viscosity driven from top surface to sensor surface

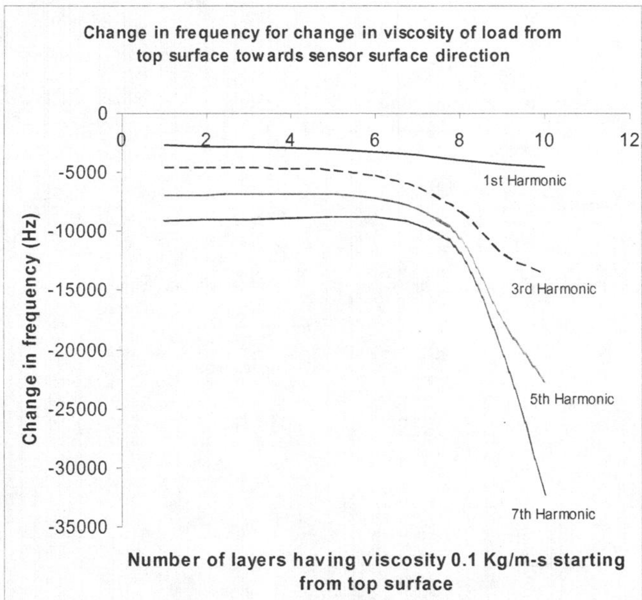

Figure 13. Response of sensor at various harmonics for process shown in Figure 12

A different trend is observed (Figure 13) in such kind of process than the process shown in Figure 10. Thus, combining all the three processes shown (Figure 8, Figure 10, Figure 12) one can identify variety of processes and also obtain information at each individual interfaces. Also, the response of piezoelectric sensor depending on the depth of penetration in the medium of load is useful concept in identifying various boundary driven processes.

IV. CONCLUSION AND FUTURE WORK

We have developed a general model for multi-layer structure loaded on piezoelectric TSM sensor. Depending on the change in material properties of the load, various signatures of the response of piezoelectric sensor can be obtained, which can help identifying interfacial processes. Various harmonics measured simultaneously can provide information at various depths and boundaries as shown by three hypothetical processes simulated in our model. Future work includes understanding these signatures, and developing a bank of database for all the signatures, which can be later used to identify or match some unknown process.

REFERENCES

[1] G. Sauerbrey, Z. Phys. 155, 206 (1959)
[2] C. E. Reed, K. K. Kanazawa, and J. H. Kaufman, J. Appl. Phys. 68, 1993 (1990)
[3] H. L. Bandey, S. J. Martin, R. W. Cernosek, Anal. Chem. 71, 2205 (1999)
[4] V. E. Granstaff, S. J. Martin, J. Appl. Phys., 75, 1319 (1993)
[5] J. F. Rosenbaum, Bulk Acoustic Wave Theory and Devices (Artech House, Boston, 1988)
[6] D. S. Ballentine, Acoustic Wave Sensors (Academic Press, MA, USA 1997)
[7] Cote, G.L.; Lec, R.M.; Pishko, M.V, Sensors Journal, IEEE, Vol.3(3), 251 – 266, June 2003
[8] Barbee, K. Sun Kwoun Lec, R.M. Sorial, J. Sorial, Frequency Control Symposium and PDA Exhibition, IEEE International, 260-267 (2002)
[9] Kwoun, S.J., Lec, R.M., Han, B., Ko, F.K., Bioengineering Conference, Proceedings of the IEEE 27th Annual Northeast, 9-10 (2001)
[10] Qiliang Zhang; Ryszard Lee; Pourrezaei, K., Frequency Control Sympposium and PDA Exhibition Jointly with the 17th European Frequency and Time Forum, Proceedings of the 2003 IEEE International, 1001-1006